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Ehyaie

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(54) **COMPACT POWER DIVIDER/COMBINER WITH FLEXIBLE OUTPUT SPACING**

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H01P 5/16 (2006.01)

(52) **U.S. Cl.**
CPC ... ***H01P 5/12*** (2013.01); ***H01P 5/16*** (2013.01)

(58) **Field of Classification Search**
CPC H01P 5/12; H03H 7/46
USPC 333/124–129, 132, 134
See application file for complete search history.

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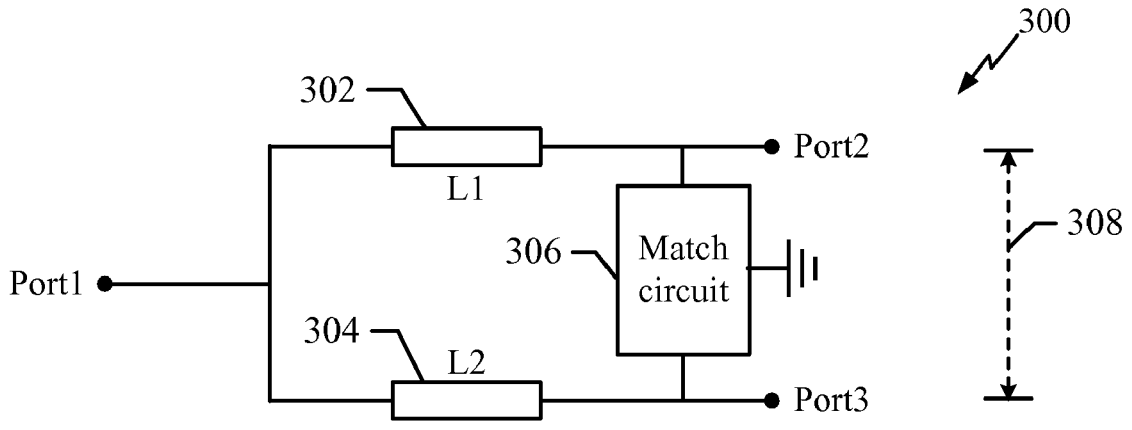
(57) **ABSTRACT**

A compact power divider/combiner with flexible port spacing is disclosed. In an exemplary embodiment, an apparatus includes a three port circuit having first, second, and third ports, and a matching circuit configured to couple the second and third ports to ground. The matching circuit includes a first transmission line connected between a first port and a second port, a second transmission line connected between the first port and a third port, a first matching circuit connected between the second port and a first node, a second matching circuit connected between the first node and the third port, and a third matching circuit connected between the first node and a ground.

20 Claims, 5 Drawing Sheets



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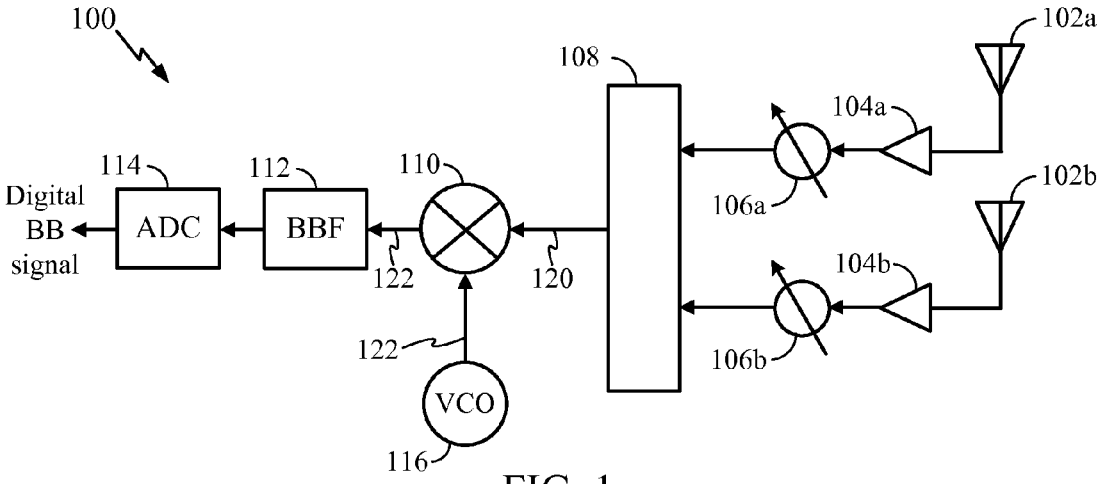

FIG. 1

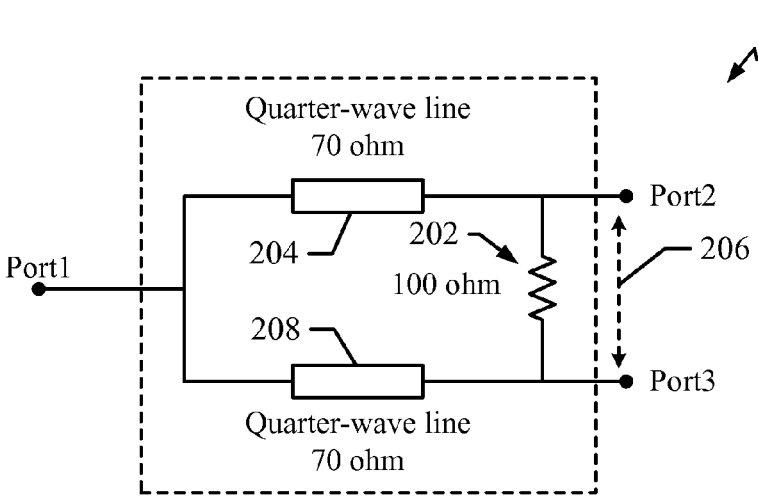

FIG. 2
Prior Art

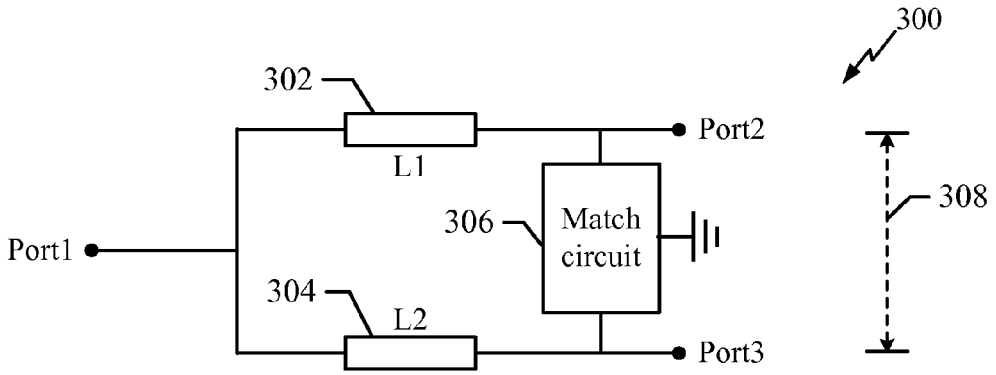

FIG. 3

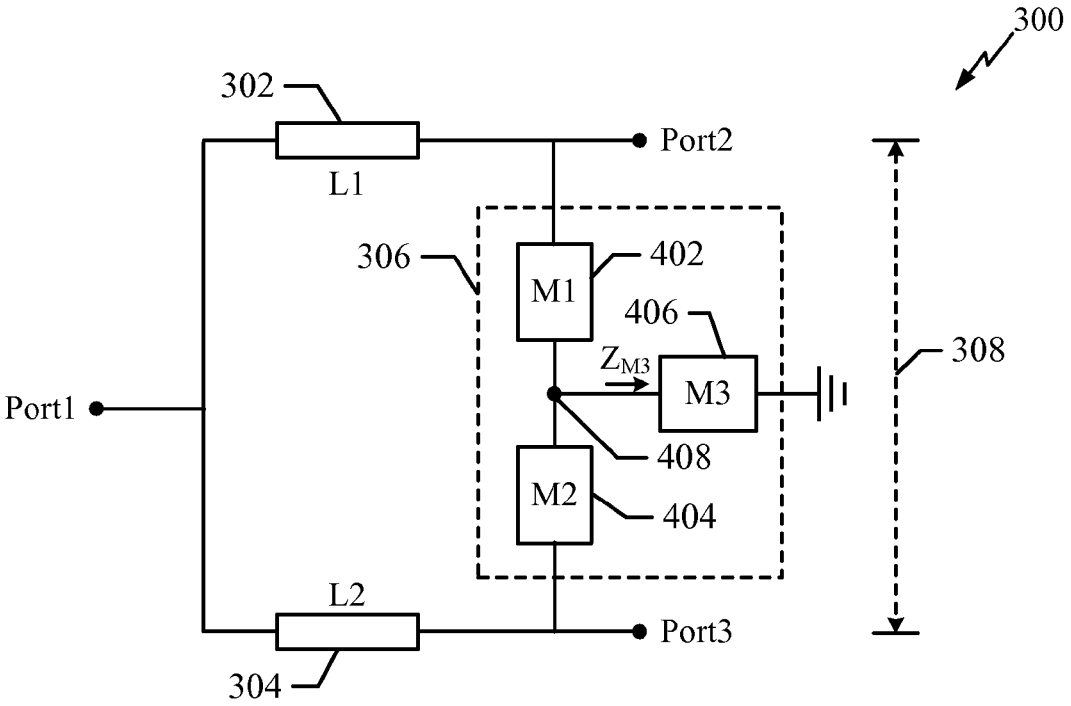
300
302
L1
Port2
306
M1
402
406
Z_{M3}
M3
308
Port1
408
M2
404
L2
Port3
304

FIG. 4

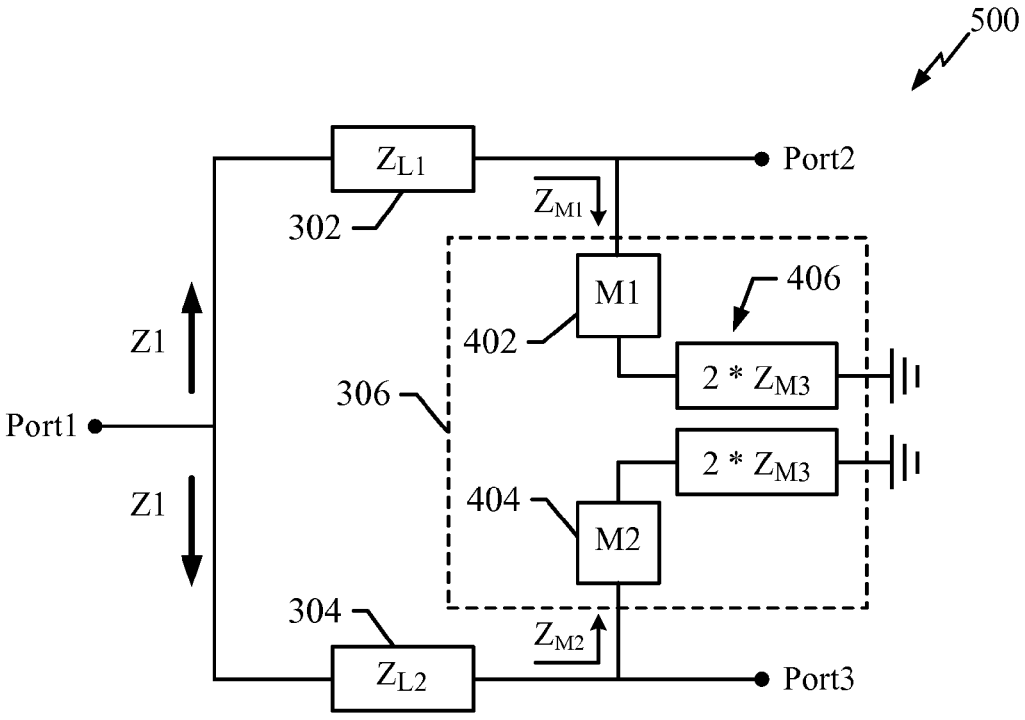
500
Z_{L1}
Port2
Z_{M1}
302
M1
406
402
Z1
2 * Z_{M3}
306
Port1
2 * Z_{M3}
Z1
404
M2
304
Z_{M2}
Z_{L2}
Port3

FIG. 5

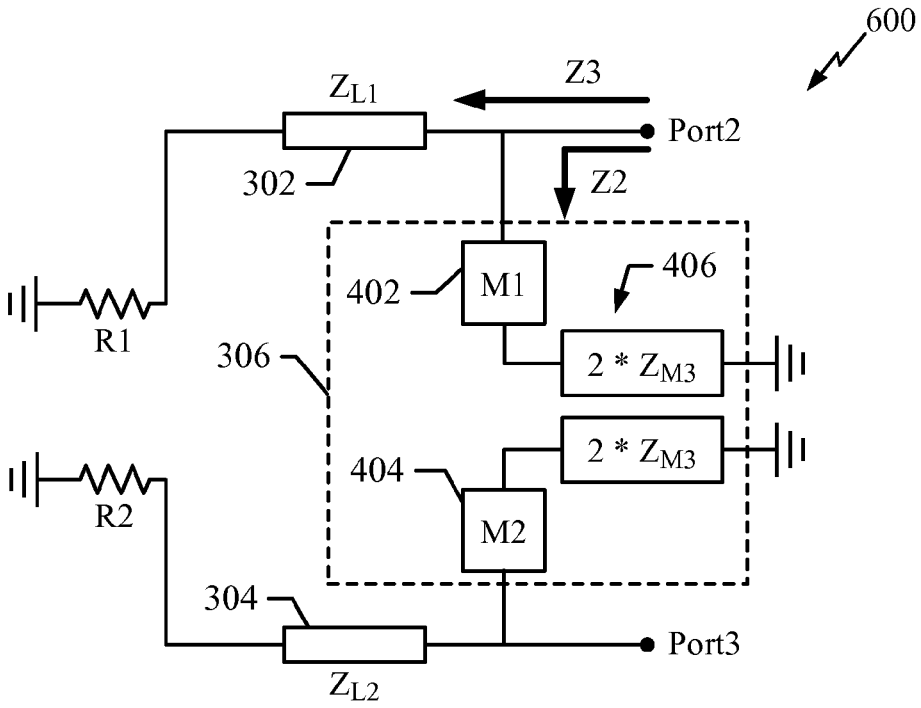
600
Z3
Z_{L1}
Port2
302
Z2
406
402
M1
R1
306
$2 * Z_{M3}$
$2 * Z_{M3}$
404
R2
M2
304
Port3
Z_{L2}

FIG. 6

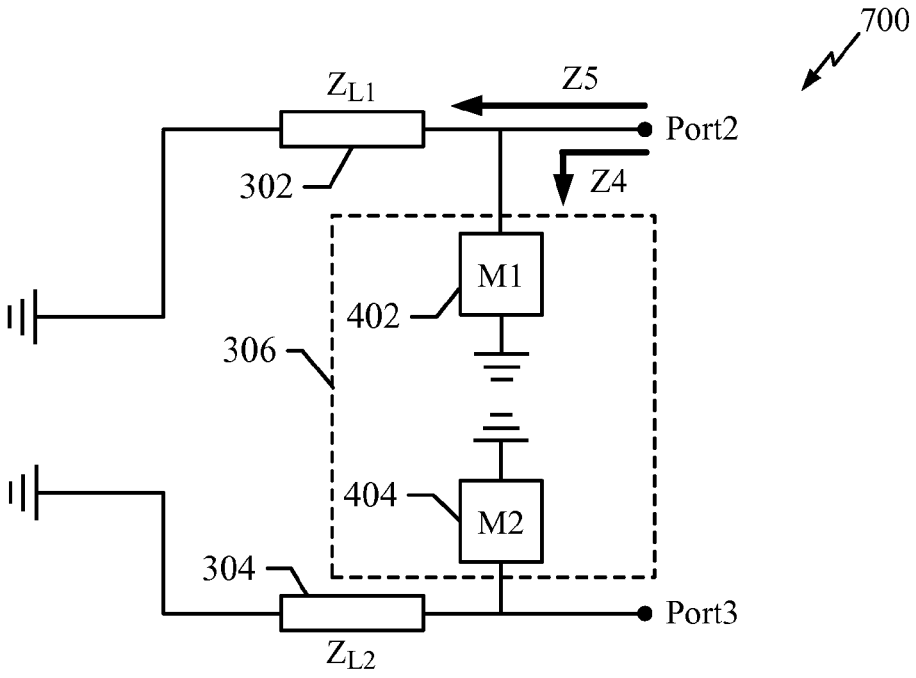
700
Z5
Z_{L1}
Port2
302
Z4
M1
402
306
404
M2
304
Port3
Z_{L2}

FIG. 7

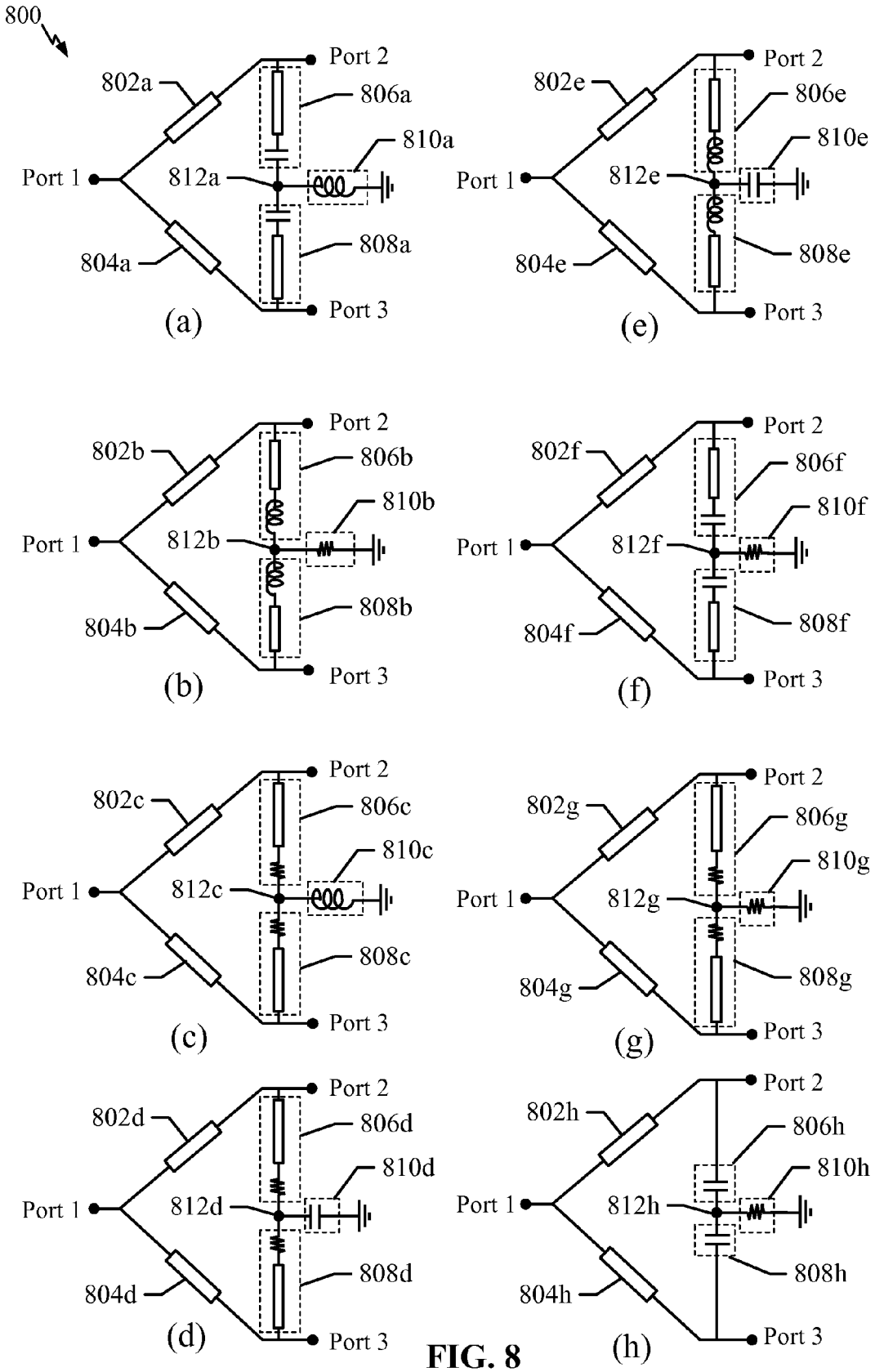
800
802a
806a
810a
Port 1
812a
808a
804a
Port 2
Port 3
(a)
802e
806e
810e
812e
808e
804e
(e)
802b
806b
810b
812b
808b
804b
(b)
802f
806f
810f
812f
808f
804f
(f)
802c
806c
810c
812c
808c
804c
(c)
802g
806g
810g
812g
808g
804g
(g)
802d
806d
810d
812d
808d
804d
(d)
802h
806h
810h
812h
808h
804h
(h)

FIG. 8

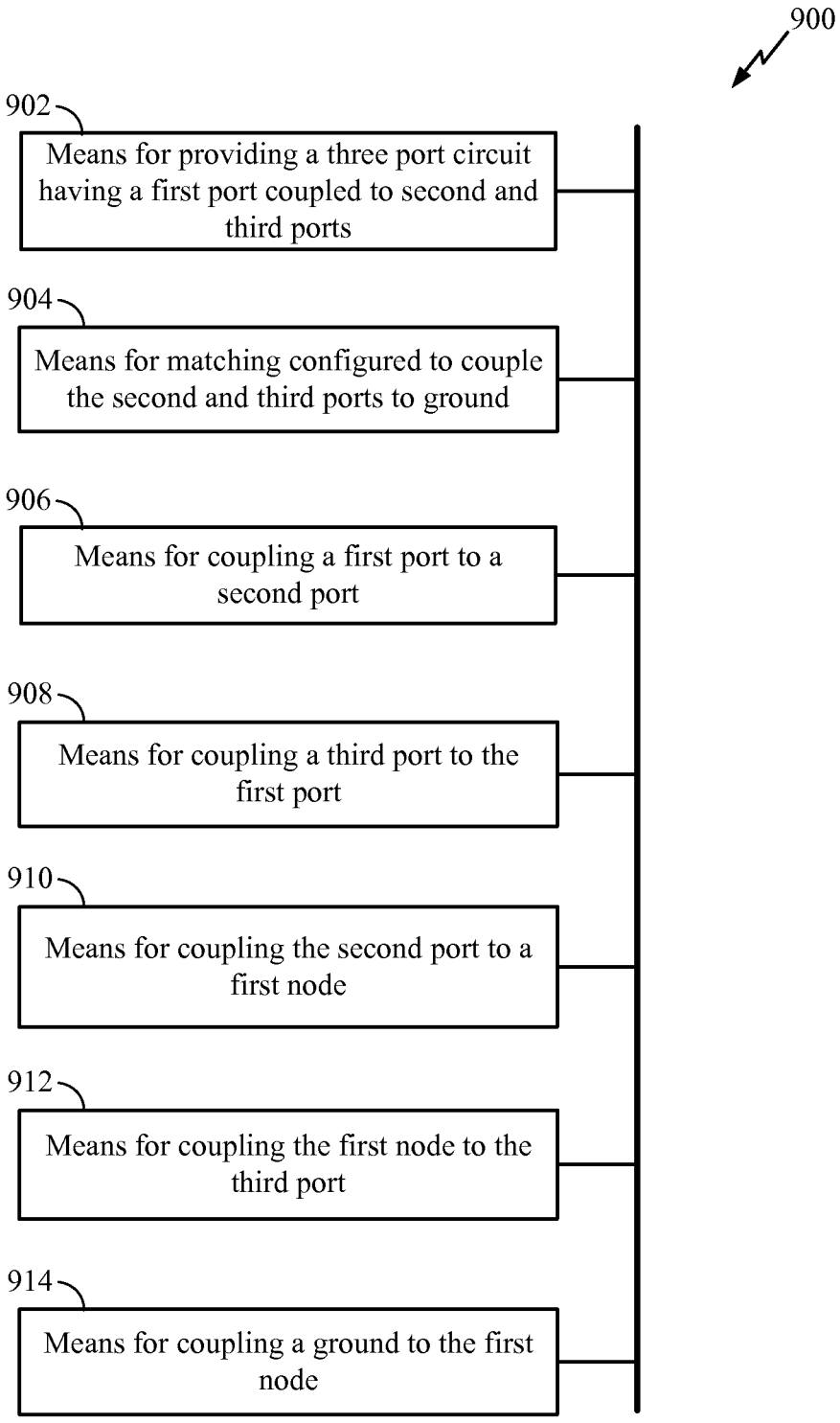
900
902
Means for providing a three port circuit having a first port coupled to second and third ports
904
Means for matching configured to couple the second and third ports to ground
906
Means for coupling a first port to a second port
908
Means for coupling a third port to the first port
910
Means for coupling the second port to a first node
912
Means for coupling the first node to the third port
914
Means for coupling a ground to the first node

FIG. 9

COMPACT POWER DIVIDER/COMBINER WITH FLEXIBLE OUTPUT SPACING

BACKGROUND

1. Field

The present application relates generally to the operation and design of analog front ends, and more particularly, to the operation and design of a power divider/combiner for use in an analog front end.

2. Background

Beamforming transceivers having multiple antennas are typically utilized to transmit and receive signals over wireless links operating at millimeter wavelengths, for instance to transmit and receive signals at 60 GHz. Almost all beamforming transceivers utilize a power divider/combiner network. During signal transmission (Tx), the divider/combiner network is used to divide the power of a transmit signal between a plurality of antennas. During signal reception (Rx), the divider/combiner network is used to combine the power of signals received from the plurality of antennas.

One conventional power divider/combiner is referred to as a Wilkinson power divider/combiner. The Wilkinson power divider/combiner is a passive network that can be shared between Tx and Rx functions, has no power consumption, good linearity, and good noise performance. Unfortunately, one problem associated with the Wilkinson power divider/combiner is that it utilizes a large circuit area. Another problem associated with the Wilkinson power divider/combiner is that its circuit implementation typically results in closely spaced port pins, which lead to increased layout complexity.

Accordingly, it would be desirable to have a simple and low cost power divider/combiner that has comparable performance to a Wilkinson divider/combiner, but utilizes smaller circuit area and provides greater flexibility to decrease layout complexity.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects described herein will become more readily apparent by reference to the following description when taken in conjunction with the accompanying drawings wherein:

FIG. **1** shows a wideband direct conversion receiver comprising an exemplary embodiment of a power divider/combiner;

FIG. **2** shows a detailed diagram of a conventional Wilkinson power divider/combiner;

FIG. **3** shows an exemplary embodiment of a divider/combiner;

FIG. **4** shows a detailed exemplary embodiment of the divider/combiner shown in FIG. **3**.

FIG. **5** shows an exemplary even mode representation of the divider/combiner shown in FIG. **4**;

FIG. **6** shows an exemplary even mode representation of the divider/combiner shown in FIG. **4**;

FIG. **7** shows an exemplary odd mode representation of the divider/combiner shown in FIG. **4**;

FIG. **8** shows exemplary embodiments of divider/combiner configurations; and

FIG. **9** shows an exemplary embodiment of a divider/combiner apparatus.

DETAILED DESCRIPTION

The detailed description set forth below in connection with the appended drawings is intended as a description of exemplary embodiments of the invention and is not intended to represent the only embodiments in which the invention can be practiced. The term "exemplary" used throughout this description means "serving as an example, instance, or illustration," and should not necessarily be construed as preferred or advantageous over other exemplary embodiments. The detailed description includes specific details for the purpose of providing a thorough understanding of the exemplary embodiments of the invention. It will be apparent to those skilled in the art that the exemplary embodiments of the invention may be practiced without these specific details. In some instances, well known structures and devices are shown in block diagram form in order to avoid obscuring the novelty of the exemplary embodiments presented herein.

FIG. **1** shows a wideband direct conversion receiver **100** employing RF beamforming for use in a wireless device. Multiple antennas **102**(*a-b*) each receive wideband RF signals that are input to low noise amplifiers **104**(*a-b*). The outputs of the LNAs **104** are input to phase shifters **106**(*a-b*) that phase shift these received RF signals with selected amounts of phase shift associated with a desired beam pattern/direction. By providing the appropriate phase shifts, the phase shifters **106** can generate a selected beam pattern/direction that is selected from a plurality of possible beam patterns/direction.

The phase shifted signals output from the phase shifters **106** are combined by a novel divider/combiner **108** to generate an RF wideband beamformed signal **120**. The beamformed signal **120** is input to a mixer **110** that performs a down-conversion using a local oscillator (LO) signal **122** generated by a voltage controlled oscillator (VCO) **116**. The mixer **110** generates a baseband beamformed signal **122** that is filtered by a baseband filter (BBF) **112** and digitized by an analog to digital filter (ADC) **114** to generate a digital BB signal that can be further processed by the wireless device.

In various exemplary embodiments, the novel divider/combiner **108** is configured to utilize a smaller circuit area and provides greater flexibility for decrease layout complexity when compared to convention divider/combiners. It should also be noted the divider/combiner **108** also operates to process signals flowing the reverse direction, such as during signal transmission. Thus, during transmission, the divider/combiner **108** receives a transmit signal as input and divides the power of the transmit signal to multiple outputs that are connected to multiple phase shifters. The phase shifters then provide selected amounts of phase shift to form a desired transmission beam pattern.

FIG. **2** shows a conventional Wilkinson power divider/combiner **200**. For example, the divider/combiner **200** may be used in the receiver **100** shown in FIG. **1**. The divider/combiner **200** comprises two nodes (Port2, Port3) connected together with a 100 ohm resistor **202**. The resistor **202** is typically very small, which means that the spacing **206** between two nodes (Port2, Port3) is generally very small. In many implementations, it may not be feasible to have the nodes (Port2, Port3) very close together, and therefore the implementation of the divider/combiner **200** provides less flexibility resulting in increased layout complexity.

The divider/combiner **200** also comprises transmission lines **204**, **208** which provide characteristic impedances of 70 ohm. There is a relationship between impedance and size of the transmission lines **204**, **208**. For example, as the impedance of the transmission line **204** becomes larger the circuit area required for the transmission line **204** may also increase. Therefore, by utilizing 70 ohm transmission lines and the small resistor **202**, the divider/combiner **200** has the disadvantages of large circuit area and increased layout complex-

ity. Accordingly, in various exemplary embodiments, the novel power divider/combiner **108** has a smaller circuit area and provides greater flexibility for decreased layout complexity when compared to the Wilkinson divider/combiner **200**.

FIG. **3** shows an exemplary embodiment of a divider/combiner **300**. The divider/combiner **300** is configurable to utilize smaller circuit area and provide increased flexibility for decreased layout complexity when compared to the conventional Wilkinson divider/combiner **200** shown in FIG. **2**. The divider/combiner **300** comprises a first transmission line **302** connected between a first port (Port 1) and a second port (Port 2). The divider/combiner **300** also comprises a second transmission line **304** connected between Port 1 and a third port (Port 3). The divider/combiner **300** also comprises a matching circuit **306** coupled between coupled between Port 2 and Port 3. The matching circuit **306** is also coupled to ground. Thus, the divider/combiner **300** comprises a three port circuit having first, second, and third ports and includes a matching circuit configured to couple the second and third ports to ground.

In an exemplary embodiment, the matching circuit **306** allows for increased spacing **308** between Port 2 and Port 3 thereby providing increased layout flexibility. Furthermore, the impedances of the transmission lines **302**, **304** and the matching circuit **306** are adjustable allowing the size of the transmission lines **302**, **304** to be reduced thereby resulting in a smaller overall circuit when compared to the divider/combiner **200** shown in FIG. **2**.

FIG. **4** shows a detailed exemplary embodiment of a divider/combiner **300**. The divider/combiner **300** is configurable to utilize smaller circuit area and provide increased flexibility for decreased layout complexity when compared to the conventional Wilkinson divider/combiner **200** shown in FIG. **2**. The transmission line **302** has a length (L1) and a characteristic impedance of (Z_{L1}). The line **304** has a length (L2) and a characteristic impedance of (Z_{L2}). The matching circuit **306** comprises a first matching circuit (M1) **402** and a second matching circuit (M2) **404** connected in series between Port 2 and Port 3. Third matching circuit (M3) **406** is connected between a first node **408** and a ground. The third matching circuit **406** has an input impedance value defined as (Z_{M3}).

In an exemplary embodiment, implementation of the first **402** and second **404** matching circuits provides increased spacing **314** between Port 2 and Port 3 thereby providing increased layout flexibility. The impedances of the transmission lines **302**, **304** and matching circuits **402**, **404**, and **406** can also be adjusted to reduce the size of the transmission lines **302**, **304**, thereby resulting in a smaller overall circuit when compared to the divider/combiner **200** shown in FIG. **2**. Adjustments to the impedances of the divider/combiner **300** to obtain reduced circuit size can be performed based on the results of even and odd mode analysis provided below.

Even Mode Analysis

FIG. **5** shows an exemplary even mode representation **500** of the divider/combiner **300** with respect to Port 1. In this representation, the impedances of the transmission lines **302**, **304** and the matching circuits **402**, **404** and **406** are configured so that they combined to match an impedance (Z1) seen at Port 1. As illustrated in FIG. **5**, the matching circuit M3 **406** is divided to provide two separate impedances that combined to form the input impedance Z_{M3}.

In an exemplary embodiment, the above impedances are set so that the impedance Z1 is equivalent to 100 ohms, and thus the combined impedance seen at Port 1 would be 50 ohms. It should be noted that a range of impedance values can be used to obtain a combined impedance seen at Port 1 that is different from 50 ohms By adjusting the impedances of the matching circuits M1 **402**, M2 **404** and M3 **406**, it is possible to adjust the size of the transmission lines **302**, **304** while achieving the desired Port 1 impedance. For example, the size of the transmission lines **302**, **304** can be reduced by adjusting the impedances of the matching circuits **402**, **404**, and **406** to achieve the desired combined impedance at Port 1. As a result, the transmission lines **302**, **304** may be set to provide smaller impedances and have corresponding smaller sizes.

FIG. **6** shows an exemplary even mode representation **600** of the novel divider/combiner **300** with respect to Ports 2 and 3. Referring to Port 2, the impedances of the transmission lines **302**, **304** and the matching circuits **402**, **404** and **406** are configured so that impedances (Z2 and Z3) seen at Port 2 form a parallel combination to obtain a desired impedance value. For example, if the desired impedance at Port 2 is 50 ohms then the parallel combination of the impedances Z2 and Z3 is set to 50 ohms as follows.

$$50 = Z2 \,||\, Z3 \text{ (parallel combination of Z2 and Z3)}$$

Thus, the size of the transmission lines **302**, **304** can be reduced by adjusting the impedances of the matching circuits **402**, **404**, and **406** to achieve the desired combined impedance at Port 2. As a result, the transmission lines **302**, **304** may be set to provide smaller impedances and have corresponding smaller sizes.

Odd Mode Analysis

FIG. **7** shows an exemplary odd mode representation **700** of the novel divider/combiner **300** with respect to Ports 2 and 3. Referring to Port 2, the matching circuit **406** is set to have zero impedance and is therefore replaced with a short to ground. The impedances of the lines **302**, **304** and the matching circuits **402**, **404** are configured so that impedances (Z4 and Z5) seen at Port 2 form a parallel combination to obtain a desired impedance value. For example, if the desired impedance at Port 2 is 50 ohms then the parallel combination of the impedances Z4 and Z5 is set to 50 ohms as follows.

$$50 = Z4 \,||\, Z5 \text{ (parallel combination of Z4 and Z5)}$$

Therefore, the novel divider/combiner **300** can be configured by adjusting impedances of the matching circuits **402**, **404**, and **406** to reduce the impedance of the transmission lines **302**, **304**, and thereby reduce the required chip area of the transmission lines **302** and **304**. The divider/combiner **300** is also configured to increase the port spacing between Ports 2 and 3 to provide greater layout flexibility as compared to the divider/combiner **200** shown in FIG. **2**.

FIG. **8** shows exemplary embodiments of divider/combiner configurations **800**. In each configuration, Port 1 is coupled to Port 2 by transmission line **802** and Port 1 is coupled to Port 3 by transmission line **804**. A first matching circuit **806** is coupled between Port 2 and node **812** and a second matching circuit **808** is coupled between Port 3 and the node **812**. A third matching circuit **810** is coupled between the node **812** and ground.

In the various configurations, the matching circuits **806**, **808** and **810** comprise transmission lines, inductors, capacitors and/or resistors. For example, the matching circuit **806***a* comprises a transmission line and a capacitor, the matching circuit **806***b* compromises a transmission line and an inductor, and the matching circuit **806***c* comprises a transmission line and a resistor. It should be noted that the matching circuits **806** and **808** need not comprises a transmission line. For example, the matching circuits **806***h* and **808***h* comprises only capacitors.

All the novel divider/combiner configurations shown in FIG. **8** can be configured by adjusting impedances of the

matching circuits **806**, **808**, and **810** to reduce the required chip area of the transmission lines **802** and **804** and to increase the port spacing between Ports 2 and 3 to provide greater layout flexibility as compared to the divider/combiner **200** shown in FIG. **2**.

FIG. **9** shows an exemplary embodiment of a divider/combiner apparatus **900**. For example, the apparatus **900** is suitable for use as the divider/combiner **300** shown in FIG. **4** or the divider/combiner **108** shown in FIG. **1**. In an aspect, the apparatus **900** is implemented by one or more modules configured to provide the functions as described herein. For example, in an aspect, each module comprises hardware and/or hardware executing software.

The apparatus **900** comprises a first module comprising means (**902**) for providing a three port circuit having a first port couple to second and third ports, which in an aspect comprises the power divider/combiner **300**.

The apparatus **900** comprises a second module comprising means (**904**) for matching configured to couple the second and third ports to ground, which in an aspect comprises the matching circuit **306**.

The apparatus **900**, the means **904** for matching comprises a third module comprising means (**906**) for coupling a first port to a second port, which in an aspect comprises the transmission line **302**.

The apparatus **900**, the means **904** for matching also comprises a fourth module comprising means (**908**) for coupling a third port to the first port, which in an aspect comprises the transmission line **304**.

The apparatus **900** the means **904** for matching also comprises a fifth module comprising means (**910**) for coupling the second port to a first node, which in an aspect comprises the matching circuit **402**.

The apparatus **900** the means **904** for matching also comprises a sixth module comprising means (**912**) for coupling the first node to the third port, which in an aspect comprises the matching circuit **404**.

The apparatus **900**, the means **904** for matching also comprises a seventh module comprising means (**914**) for coupling a ground to the first node, which in an aspect comprises the matching circuit **406**.

Those of skill in the art would understand that information and signals may be represented or processed using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof. It is further noted that transistor types and technologies may be substituted, rearranged or otherwise modified to achieve the same results. For example, circuits shown utilizing PMOS transistors may be modified to use NMOS transistors and vice versa. Thus, the amplifiers disclosed herein may be realized using a variety of transistor types and technologies and are not limited to those transistor types and technologies illustrated in the Drawings. For example, transistors types such as BJT, GaAs, MOSFET or any other transistor technology may be used.

Those of skill would further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the exemplary embodiments of the invention.

The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Computer-readable media includes both non-transitory computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A non-transitory storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD),

floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

The description of the disclosed exemplary embodiments is provided to enable any person skilled in the art to make or use the invention. Various modifications to these exemplary embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the invention is not intended to be limited to the exemplary embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. An apparatus comprising:

a three port circuit having a first port coupled to a second and third ports; and

a matching circuit connected in series between the second and third ports, the matching circuit configured to couple the second and third ports to ground, the apparatus forming a bidirectional power combiner/divider.

2. The apparatus of claim **1**, the matching circuit comprising:

a first matching circuit coupled between the second port and a first node;

a second matching circuit coupled between the first node and the third port; and

a third matching circuit coupled between the first node and the ground.

3. The apparatus of claim **2**, further comprising:

a first transmission line coupled between the first port and the second port; and

a second transmission line coupled between the first port and the third port.

4. The apparatus of claim **3**, the first and second transmission lines and the first, second, and third matching circuits configured to provide a combined impedance value seen at the first port that is matched to a selected characteristic impedance value.

5. The apparatus of claim **4**, the selected characteristic impedance value is set to 50 ohms.

6. The apparatus of claim **3**, the first, second, and third matching circuits configured to adjust sizes of the first and second transmission lines.

7. The apparatus of claim **2**, the first and second matching circuits are configured to increase spacing between the second and third ports.

8. The apparatus of claim **3**, the first and second transmission lines and the first, second, and third matching circuits configured to provide a combined impedance value seen at the second port that is matched to a selected characteristic impedance value.

9. The apparatus of claim **8**, the selected characteristic impedance value is set to 50 ohms.

10. The apparatus of claim **1**, the apparatus forming a bidirectional passive power combiner/divider.

11. The apparatus of claim **10**, the bidirectional passive power combiner/divider configured for use in a transceiver.

12. An apparatus comprising:

means for providing a three port circuit having a first port coupled to second and third ports; and

means for matching connected in series between the second and third ports, the means for matching configured to couple the second and third ports to ground, the apparatus forming a bidirectional power combiner/divider.

13. The apparatus of claim **12**, the means for matching comprising:

means for coupling the second port and a first node;

means for coupling the first node and the third port; and

means for coupling the ground to the first node.

14. The apparatus of claim **13**, further comprising:

means for coupling a first transmission line between the first and second ports; and

means for coupling a second transmission line between first and third ports.

15. The apparatus of claim **14**, the first transmission line, the second transmission line, the means for coupling the second port, the means for coupling the first node, and the means for coupling the ground configured to provide a combined impedance value seen at the first port that is matched to a selected characteristic impedance value.

16. The apparatus of claim **14**, the means for coupling the second port, the means for coupling the first node, and the means for coupling the ground configured to adjust sizes of the first and second transmission lines.

17. The apparatus of claim **14**, the means for coupling the second port, the means for coupling the first node configured to increase spacing between the second and third ports.

18. The apparatus of claim **14**, the first transmission line, the second transmission line, the means for coupling the second port, the means for coupling the first node, and the means for coupling the ground configured to provide a combined impedance value seen at the second port that is matched to a selected characteristic impedance value.

19. The apparatus of claim **12**, the apparatus forming a bidirectional passive power combiner/divider.

20. The apparatus of claim **19**, the bidirectional passive power combiner/divider configured for use in a transceiver.

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